CHAPTER 23

ELECTROMAGNETIC INDUCTION (PART 2)

The magnetic field around a single conductor and a coil was examined in Chapter 21. For convenience, the field was said to be a series of lines of force. These lines followed the rules of magnetic lines of force stated in Chapter 20. The pattern of the fields was obtained when the current through the conductors had reached a steady state condition. In the case of a coil, however, the exact nature of how the individual fields around each conductor combine during the period when the current is changing, is not defined. Many theories have been advanced and one acceptable to this level of study will be used in this book.

23.1 INDUCTANCE (L)

Inductance is a physical property, much the same as resistance. Any device which is capable of producing a flux contains inductance. The inductance of a coil is proportional to the number of turns in the coil squared, the permeability of the magnet circuit in the coil, and the cross sectional area of the magnetic circuit. It is also inversely proportional to the length of the magnetic circuit. The unit for inductance is the henry (H) and the equation for determining the value of inductance for a coil is given by —

$$L = \frac{N^2 \mu A}{l} \text{ henrys}$$

Where

L = inductance in henrys

N = number of turns in the coil

μ = permeability of the magnetic circuit

A = cross-sectional area of the magnetic circuit in metres squared

l = length of the magnetic circuit in metres

In chapter 21 it was stated that the permeability of a material could be broken up into two parts, the permeability of free space, μ_o $(4 \pi \times 10^{-7})$ and the relative permeability μ_r. Substituting these in the inductance equation gives -

$$L = \frac{N^2 \mu_o \mu_r A}{l} \text{ henrys}$$

It should be noted that inductance is a property that is built into a component and is not dependant on voltage or current.

Example 23.1

An air cored coil is 200 mm long, has a c.s.a. of 50 mm^2 and contains 1000 turns. Calculate its inductance.

$N = 1000$

$A = 50 \times 10^{-6}$ m^2

$l = 200 \times 10^{-3}$ m

$\mu_o = 4\pi \times 10^{-7}$

$\mu_r = 1$

$L = ?$ henrys

$$L = \frac{N^2 \mu_o \mu_r A}{l}$$

$$= \frac{10^3 \times 10^3 \times 4\pi \times 10^{-7} \times 50 \times 10^{-6}}{200 \times 10^{-3}}$$

$$= 0.314 \text{ mH}$$

Example 23.2

Calculate the number of turns of a solenoid that has a length of 200 mm, an area of 500 mm^2 and a core whose **absolute** permeability is 1 x 10^{-4} if the inductance of the solenoid is 0.25 henrys.

$$L = 0.25\text{ H}$$
$$A = 500 \times 10^{-6}\text{ m}^2$$
$$l = 200 \times 10^{-3}\text{m}$$
$$\mu = 1 \times 10^{-4}$$
$$N = ?$$

$$L = \frac{N^2 \mu A}{l}$$
$$N^2 = \frac{L l}{\mu A}$$
$$= \frac{0.25 \times 200 \times 10^{-3}}{1 \times 10^{-4} \times 500 \times 10^{-6}}$$
$$10^6$$
$$N = \sqrt{10^6}$$
$$= 1000\text{ turns}$$

23.2 SELF-INDUCED e.m.f.

Switching on current from a d.c. supply to a single conductor builds up around the conductor a magnetic field consisting of a series of concentric lines of force (Chapter 21). The lines of force spread out from the centre of the conductor into the space surrounding the conductor. When the current in the conductor is switched off, the magnetic field collapses, or closes, back to the centre of the conductor. During the switching on and off process the magnetic field is actually a moving magnetic field as it expands and contracts about the centre of the conductor. In a coil, the conductors, or turns are wound side by side. Current in one turn will create a magnetic field whose lines of force or influence will cut across adjacent conductors as the current in the coil is switched on and off. (Figure 23.1).

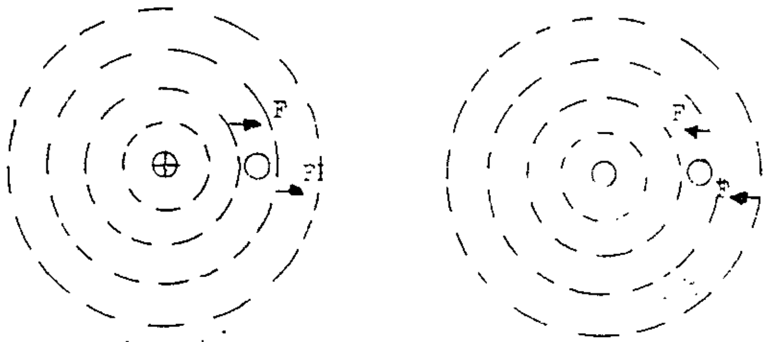


Figure 23.1

increasing

decreasing

As the current in the coil is the same in each conductor, the current in the adjacent conductor will also have a magnetic field which cuts across the first conductor. There is relative motion between the magnetic field of each conductor and its neighbouring stationary conductor. From Faraday Law of electro-magnetic induction, when relative motion exists between a magnetic field and a conductor an e.m.f. is induced in that conductor. From this it can be seen that each conductor of the coil has an e.m.f. induced into it by its adjacent conductors.

Because the e.m.f. is produced within the coil and not from an external source it is called a self induced e.m.f. The direction of the self induced e.m.f. can be determined from Fleming's Right Hand Rule (Chapter 21) as shown in Figure 23.2

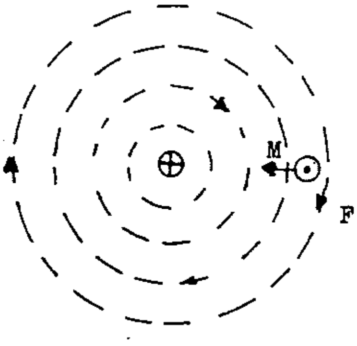


Figure 23.2

The e.m.f. induced in the conductor by the magnetic field is in the opposite direction to the applied e.m.f. It opposes the applied e.m.f. and for this reason, it is often called the back e.m.f. Self induced e.m.f.'s will only occur when there is a changing magnetic field near a conductor. A constant magnetic field will produce zero self induced e.m.f.

23.2 SELF INDUCTION

In Chapter 8 inductors were mentioned briefly as one of the components that may appear in an electrical circuit. Inductors, coils and solenoids have the property of inductance, which is the ability to create a magnetic field. If an inductor is supplied with a changing current that causes its magnetic field to increase or decrease a back e.m.f. will be induced into the inductor. The property that produces this back e.m.f. is known as self inductance and the e.m.f. is said to be due to the self induction of the coil. Self induction (symbol L) has the same units as induction, namely, the henry.

The symbol for self inductance is the capital letter 'L'.

23.3 MUTUAL INDUCTANCE

If two coils are placed close together so that the lines of force created by one coil, whose current is changing, intersect the conductors of the second coil, an e.m.f. will be induced in the second coil. (Figure 23.3)

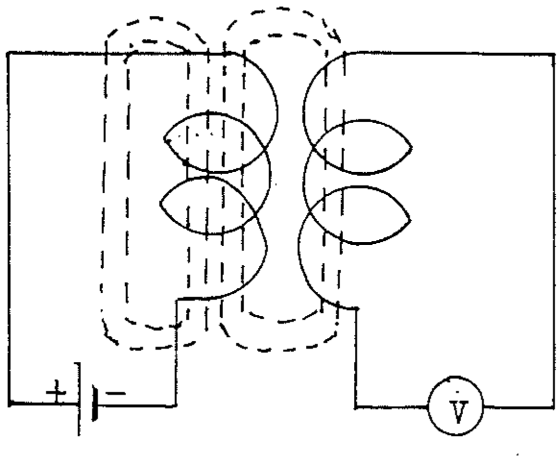


Figure 23.3

The e.m.f. produced in the second coil is due to the property of mutual inductance between the coils. The lines of force spreading out from the conductors in the first coil move across conductors in the first and second coils in the same direction. Therefore, the direction of the induced e.m.f. in the second coil must be the same as that of the self induced e.m.f. in the first coil. The symbol for mutual inductance is 'L'. and its units are henrys.

23.4 OPPOSITION TO CURRENT BY INDUCTANCE

When current creates a magnetic field in a coil, it has to overcome the opposition produced by the inductance of the coil. This causes a delay in the current reaching a steady state or maximum value. (Figure 23.4).

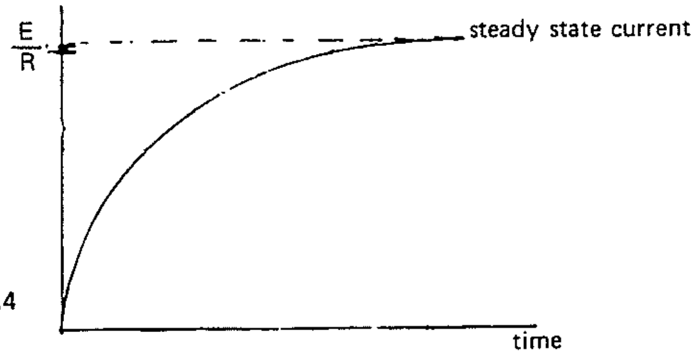


Figure 23.4

The time taken for the current to rise to 63% of the final steady state is called the time constant of the circuit (τ). In a circuit containing resistance and inductance only, the time constant is equal to the inductance divided by the resistance.

$$\tau = \frac{L}{R} \text{ seconds}$$

It takes approximately five time constants for a steady state condition to be reached by the current. (Figure 23.5).

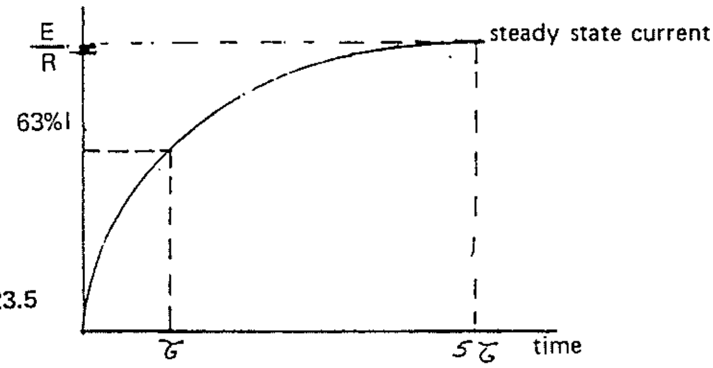


Figure 23.5

When the d.c. supply to the coil is switched off, the current in the coil decreases as shown in Figure 23.6.

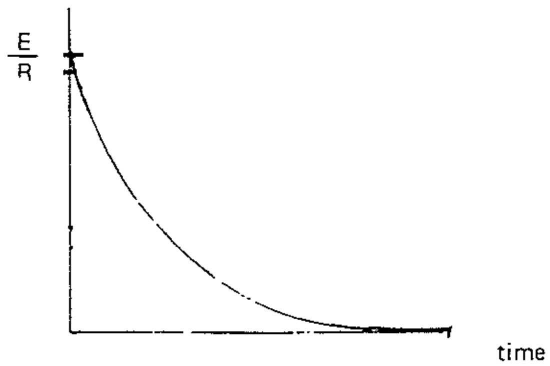
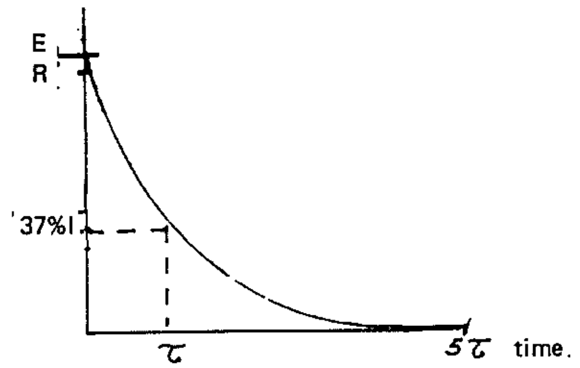


Figure 23.6

The time taken for the current in the coil to decrease by 63% of the initial voltage is again the time constant and is equal to $\frac{L}{R}$ (Figure 23.7). Time constants are useful in comparing the expected operation of components

Figure 23.7



Example 23.3

A coil having a resistance of 1 k Ω and an inductance of one henry is connected in series to a 200 volt d.c. supply. Calculate –

(a) the time constant of the circuit

(b) the voltage drop across the coil after one time constant.

$R = 1$ kohm

$L = 1$ H

$E = 200$ V

$\tau = ?$ sec

$E_L = ?$ V

$$\tau = \frac{L}{R}$$

$$= \frac{1}{10^3}$$

$= 0.001$ seconds

$$E = \frac{63}{100} \times 200$$

$= 126$ V

Example 23.4

When an R.L series circuit is connected to a d.c. supply the voltage across the R.L. section reaches its time constant value of 31.5 volts in 0.01 seconds. If the value of the resistance in the circuit is 1 kΩ calculate the applied e.m.f. and inductance of the circuit.

$\tau = 31.5$ V

$\tau = 0.01$ S

$R = 1\ k\Omega$

$E = ?$ V

$L = ?$ H

$\tau = E \times 0.63$

$$E = \frac{\tau}{0.63}$$

$$= \frac{31.5}{0.63}$$

$= 50$ V

$$\tau = \frac{L}{R}$$

$= R\,\tau$

$= 10^3 \times 0.01$

$= 10$ H

Electrical energy is converted to magnetic energy and back again to electrical energy, when the supply to a coil is switched on and off. As no energy is expended, only converted, in the process the reaction of inductance to current flow does not consume power. Inductance only effects current while there is a **changing** magnetic field.

Equations in this chapter

(1) $L = \dfrac{N^2 \mu A}{l}$

(2) $L = \dfrac{N^2 \mu_o \mu_r A}{l}$

(3) $\tau = \dfrac{L}{R}$

TUTORIALS 1.23

(1) An air cored coil has an inductance of 0.0045 henry. The coil has 1500 turns and a c.s.a. of 500 mm^2. Calculate the length of the core.

(2) A solenoid whose inductance is 0.0804 henry has a length of 500 mm and a c.s.a. of 50 mm^2. If the solenoid is wound on a core whose relative permeability is 1000, calculate the turns of the solenoid.

(3) Calculate the inductance of a coil that has 500 turns, a c.s.a. of 75 mm^2 and a length of 225 mm if the core material of the coil has a relative permeability of 2000.

(4a) Determine the time constant of a d.c. series circuit consisting of an 4.7 k Ω resistor and 20 mH inductor.

b) If the circuit is connected to a 500 V source determine the voltage after one time constant.

(5) The time constant of a series circuit containing a 2.2 k Ω resistor and a inductor was found to be 11.5 seconds. Calculate the inductance in the circuit.